A STUDY
OF THE EFFECT OF DIFFERENT CONCENTRATIONS OF AIR BORNE DUST ON THE EFFICIENCY OF A MODEL PRECIPITRON

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A STUDY OF THE EFFECT OF DIFFERENT
CONCENTRATIONS OF AIR BORNE DUST
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Approved:

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INTRODUCTION

Purpose:

The purpose of this study is to determine the effect of different concentrations of air borne dust on the efficiency of a model PRECIPITRON. This study was suggested by a review of the unpublished works of Earl C. Wilson.[1] Mr. Wilson shows that the efficiency of the model PRECIPITRON used in his study increases as the concentration of air borne particles increases; however, the range of concentrations studied in his work was small as interests were along other lines.

Concentrations of air borne particles used in this study range from the maximum concentration used in Mr. Wilson's study[2] to the maximum concentration the model PRECIPITRON will precipitate without requiring excessive cleaning. Attention is also given to the sparking characteristics of the PRECIPITRON collector plate section when a relatively high concentration of air borne particles is encountered.

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[1] Earl C. Wilson, Absolute Efficiency of Electrostatic Precipitation for Collection of Siliceous Dust, M.S. Thesis, Ga. Tech, September 1950.

[2] Ibid.

Characteristics of Dust:

Figure 1 illustrates graphically the dust particles that abound in the air about us. The larger particles slowly settle or can be removed by mechanical filter systems, but the smaller particles, which are responsible for much damage and human discomfort, were until comparatively recently almost impossible to remove. The inability of mechanical filter systems to remove small particles which have little tendency to settle under gravitational action has resulted in the development of electrostatic dust precipitation equipment which is efficient in removing even the smallest size particles such as those composing the visible elements of tobacco smoke. Thus, the development of electrostatic dust precipitation equipment has made possible standards of industrial cleanliness heretofore impossible to achieve economically.

Historical Survey:

The effect of electrostatic fields on small air borne particles was first observed in 1824.[3] In 1884 Sir Oliver Lodge used electrostatic precipitation in the solution of a lead smelting problem.[4] However, it was not until 1906[5] that the first practical electrostatic precipitator was developed by Dr. Cottrell. The Cottrell precipitator has since been used

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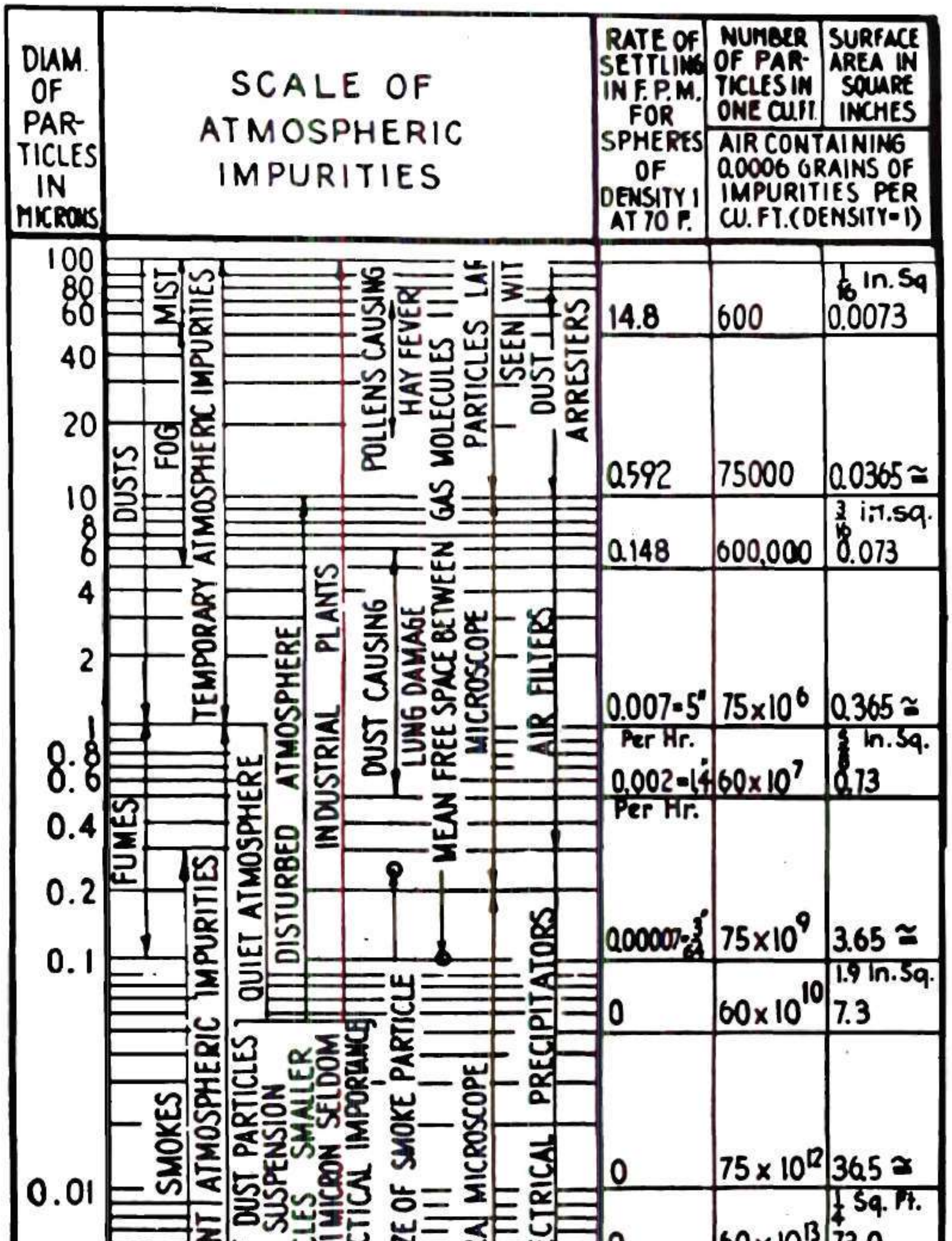
[3] C. H. McWhirter and R. P. Posey, Electrostatic Air Cleaning in the Textile Industry. A paper presented to the A.I.E.E. Southern District Meeting in Birmingham, Ala., November 1948.

[4] Ibid.

[5] Ibid.



Compiled from Stokes Law - Governing Rate of fall in relation to Particle Size

FIGURE 1

extensively in the precipitation of particles from flue gases. Many practical modifications of this precipitator have been designed and marketed. The main disadvantage of the Cottrell precipitator is that large quantities of ozone are generated, thus making its usage undesirable in ventilating systems supplying air for human consumption.

Not until 1933[6] was a practical electrostatic precipitator designed with ozone generation sufficiently low to permit its use in ventilating systems supplying air for human consumption. This new precipitator was developed at the Westinghouse Research Laboratories and is sold under the trade name of PRECIPITRON.

While the Cottrell type precipitator requires 30,000 to 100,000 volts for proper operation, the Westinghouse precipitator places a charge on the air borne particles in a chamber which is independent from that which collects the particles. By using this two-stage principle, precipitators requiring a maximum of 13,000 volts have been made possible.

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6 Ibid.

THEORY OF ELECTROSTATIC PRECIPITATION

Operating Principle of the PRECIPITRON:[7]

The electrostatic precipitator developed by Westinghouse and sold under the trade name of PRECIPITRON consists of three essential elements: the ionizer; the collector cell; and the "power-pack." The ionizer, probably the most important of these elements, places a positive electrical charge on air borne particles without the creation of excess ozone. It consists of tiny tungsten wires, on the order of a few thousands of an inch in diameter, spaced parallel and in line with grounded parallel tubes, on the order of one inch in diameter. A high positive direct current voltage, approximately 13,000 volts, on the ionizer wires causes the space between the wires and the tubes to become saturated with free positive ions. Particles pick up a positive surface charge as they are blown through this ionized space.

After passing through the ionizer section, the air then flows between alternately grounded and postively charged plates in an electrostatic chamber where the air borne particles are deposited on the grounded plates. There they remain until the plates are washed. See Figure 2 for a schematic representation of the motion of particles in the ionizer and collector sections of the PRECIPITRON.

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[7] *Ibid.*

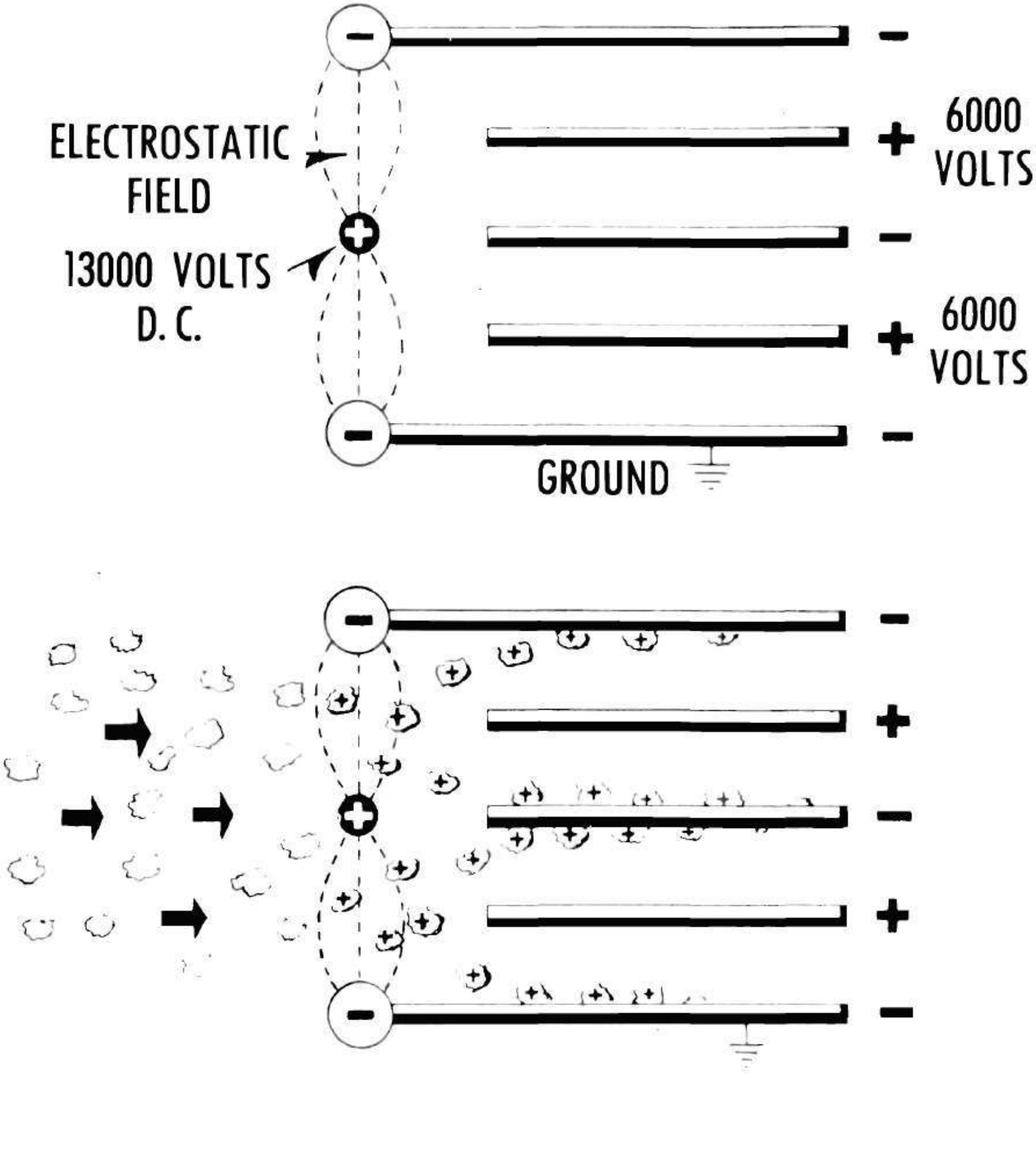
ELECTROSTATIC FIELD
13000 VOLTS D. C.
6000 VOLTS
6000 VOLTS
GROUND

FIGURE 2

The collector section is made up of metal plates parallel to the air flow. These plates are approximately 1/32 inch thick and are spaced approximately 5/16 inch apart. A positive direct current voltage of approximately 6,000 volts is applied to alternate plates.

The third essential element is the "power-pack." The most economical power-pack so far developed is a modification of the standard voltage doubling electronic circuit. Two voltage leads are brought out, one supplying 13,000 volts for the ionizer section, the other supplying 6,000 volts for the collector section. The wattage dissipation is small, being approximately 15 watts per 1000 c.f.m. of air handled.

Corona Principle:[8]

If an electric potential is applied between two conductors and gradually increased, a voltage is reached at which a hissing noise is heard, and in a dark background, a pale violet light can be seen to surround the conductors. This voltage is called the critical visual corona point. If, however, the conductors are too close together sparking will occur before this point is reached.

The corona principle is very important in the design of the ionizer section of the PRECIPITRON. Although the ionizer section is operated at sub-corona voltage, it is important that the spacing of the wires be such that sparking

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[8] F. W. Peek, Jr., Dielectric Phenomena in High Voltage Engineering (New York: McGraw-Hill Book Company, Inc., 1920), Chapter III.

does not occur when a potential is applied sufficient to produce the desired degree of ionization in the region between the conductors.

Peek[9] shows that the critical spacings, below which spark-over will occur before corona starts, are as follows for two different types of electrodes: for concentric cylinders the critical spacing is $R/r = 2.718$, where r is the inner radius and R is the outer radius; for parallel wires the critical spacing is $s/r = 5.85$, where r is the radius of the wires and s is the spacing between their centers.

Mathematical Analysis:

Definitions:[10]

1. The electric intensity at any point is the force acting on a small body charged with unit positive charge when placed at the point, the electrification of the rest of the system being undisturbed by the presence of this unit charge.

2. The electric potential at a point P exceeds that at Y by the work done by the electric field on a body charged with a unit of electricity when the latter passes from P to Y, regardless of the path followed.

Consider a small body charged with unit positive charge located in an electric field. By choosing an increment

9 Ibid., p. 29.

10 J. J. Thomson, Elements of the Mathematical Theory of Electricity and Magnetism, Fifth Edition, (Cambridge: University Press; 1921), Chapter I.

of distance dx so small that the electric intensity F may be considered to be constant throughout the distance dx, the equation for the work W done on the particle by the electric field may be written:

$$W = F\,dx,$$

where the motion of the particle and the electric intensity F are in the positive X direction. Also, by definition of electric potential:

$$W = -\,dv,$$

where dv is the increase in electric potential. Equating these values of W:

$$F\,dx = -\,dv$$

or, (1) $$F = -\frac{dv}{dx}$$

Therefore, the electric intensity or force acting on a small body possessing unit positive charge located in an electric field is equal to the negative of the voltage gradient at the point of location. It follows that the force acting on a small particle possessing a positive charge Q, and located in an electric field between two parallel plates is given by the relation:

(2) $$F' = -\frac{dv}{dx}\,Q$$

where F' = force acting on the charged particle in a direction perpendicular to the plates

$\frac{dv}{dx}$ = voltage gradient at the point at which the particle is located.

In this derivation the direction of decreasing potential is taken to be in the positive X directions. It should be noted that equation (2) gives the force acting on any charged particle in an electrostatic field. However, the proper sign must be given to the charge Q and also to the voltage gradient $\frac{dv}{dx}$.

Most propositions dealing with the forces between electrified bodies may be proven by the aid of a theorem due to Gauss.[11] This theorem may be stated as follows: the total normal electric induction over any closed surface drawn in the electric field is equal to 4π times the total charge of electricity inside the closed surface.

Now consider three equally spaced parallel planes, the middle plane possessing a quanity of electricity e units per unit area and the outer planes grounded. Neglecting end effects it is seen by symmetry (1) that the electric intensity will be normal to the planes and (2) that the electric intensity will be constant at all points in a plane parallel to and enclosed in the space between any two of the three planes. The electric intensity acts upwards in the region above the charged plane and downwards in the region below it.

To determine the magnitude of the electric intensity at any point P located in the space between the charged plane

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[11] Ibid.

and a grounded plane, draw through P a line at right angles to the planes and prolong it to a point O so that the line PO is bisected by the electrified plane. With PO as axis described a right circular cylinder bounded by planes through P and O parallel to the electrified plane. Since the electric intensity is everywhere parallel to the axis of the cylinder, and has, therefore, no normal component over the curved surface of the cylinder, the total normal induction over the surface arises entirely from the flat ends. Let F be the magnitude of the electric intensity at any point in the field and A be the area of either of the flat ends of the cylinder. Then the normal induction due to the end of the cylinder through P is FA. Also, the normal induction due to the end through O is FA and has the same sign as that due to the end through P, since both are along the outward drawn normals. Thus, the total normal induction over the surface of the cylinder is 2FA, since the normal intensity vanishes over the curved surface of the cylinder. Therefore, by Gauss's theorem

$$2FA = 4\pi eA$$

or (3) $$F = 2\pi e.$$

Taking the positive x direction to be in the direction of the grounded plates and equating the values of F given by equations (1) and (3),

$$-\frac{dv}{dx} = 2\pi e.$$

Substituting this value in equation (2) gives the force acting on a small body possessing a charge Q and located in the field between two parallel plates:

$$(4) \qquad F' = 2\pi eQ.$$

F' is the force acting on the charged body due to the electrostatic field. This force is constant at any point in the field and the line of action is at right angles to the plates.

So far nothing has been said about the force acting on a charged particle due to motion. If it is assumed that the motion of the particle in the direction of the field obeys Stokes' law,[12] the resistance it encounters is given by the following expression:

$$(5) \qquad R = kuvs$$

where
- R = force acting on the particle due to motion in the direction of the field
- k = proportionality constant 3 for spheres
- u = dynamic viscosity of the medium
- v = velocity of the particle in the direction of the field
- s = diameter of the particle.

The force R due to the motion of the particle opposes the force F'. Neglecting gravitational forces and applying Newton's law of motion

$$(6) \qquad F' - R = ma$$

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[12] J. M. Dalla Valle, Micromeritics (New York: Pitman Publishing Corporation, 1948), p. 15.

where m = mass of the particle

a = acceleration of the particle in the direction of the field.

The path followed by a charged particle in an electric field is easily obtained. Assume that the plates are perpendicular to the x-axis and that the flow is upward through them in the z-direction. Using equation (6) and writing $dx/dt = X_t$ for v and $d^2x/dt^2 = X_{tt}$ for a

$$F' - kus\frac{dx}{dt} = m\frac{d^2x}{dt^2}$$

or

$$(7) \qquad mX_{tt} + kusX_t - F' = 0$$

$$kus\frac{dX_t}{kusX_t - F'} + \frac{kus}{m}dt = 0$$

$$\ln(kusX_t - F') + \frac{kus}{m}t = \ln C_1$$

$$kusX_t - F' = C_1 \exp\left(-\frac{kus}{m}t\right)$$

$$(8) \qquad kusx - F't = C_1\frac{m}{kus}\exp\left(-\frac{kus}{m}t\right) + C_2$$

By choosing the origin so that $x = o$ at $t = o$, $C_2 = C_1\frac{m}{kus}$ and since the distance traveled in time t along the z-axis is $z = v_g t$ where v_g is the air or gas velocity, equation (8) becomes

$$(9) \quad kusx - \frac{F'}{v_g}z = C_1\frac{m}{kus}\left[1 - \exp\left(-\frac{kus}{mv_g}z\right)\right].$$

The constant of integration, C_1, is not determined since a second boundry condition is not established.

When t is very great, note that equation (9) reduces to

$$kusx - \frac{F'}{v_g}z = o$$

or

$$x = \frac{F}{kusvg}\quad z.$$

Thus the path of a charged particle obeying Stokes' law in an electrostatic field between two parallel plates approaches a straight line.

EQUIPMENT AND EQUIPMENT OPERATION

The Model PRECIPITRON:

The model PRECIPITRON used in this study is shown in Figure 3. This model conforms in every respect with a section of the commercially sold PRECIPITRON. This is the same equipment used by Wilson.[13]

The ionizer and collector plate section consists of two identical units, Figures 4 and 5, operated in parallel. Each unit is approximately 8 inches wide, 18 inches high, and 23 inches long. These units are housed in a sheet metal duct 16 inches wide, 19 inches high, and 6 feet long. A 9 inch, number 1½ SIROCCO centrifugal blower type fan driven by a 1½ h. p. motor is used to deliver air to the system. The rate at which air was delivered was controlled by a damper located in the blower intake. Ionizer and collector plate voltages are supplied by a self-contained "power-pack."

Dust Feed Apparatus:

The dust feed apparatus, Figure 6, consists of a lucite cylinder approximately 2 inches in diameter and 5 inches in length in which is fitted a piston. The piston is approximately 1 inch thick and is supported by a rod approximately

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[13] Earl C. Wilson, *loc. cit.*

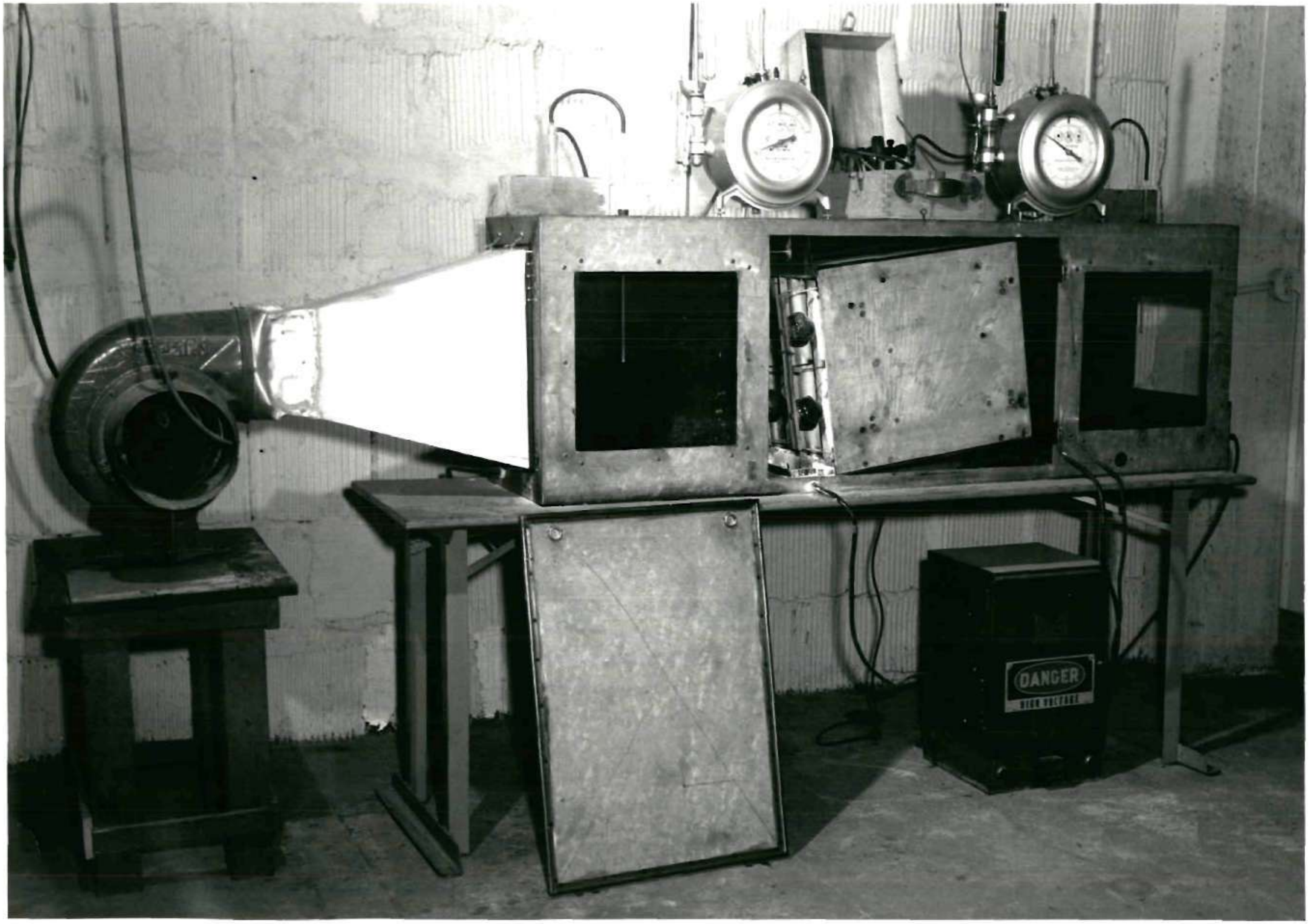


FIGURE 3

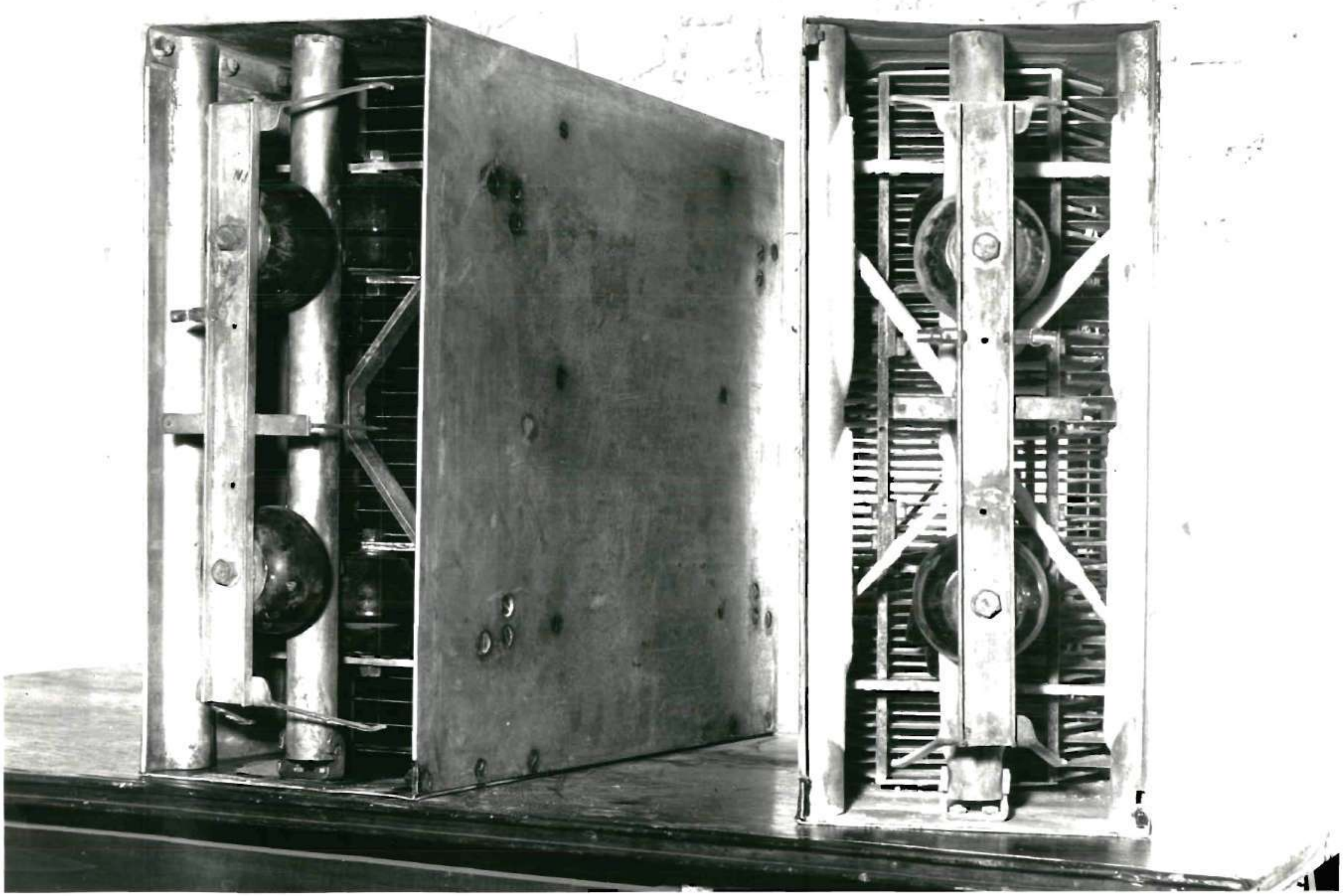


FIGURE 4

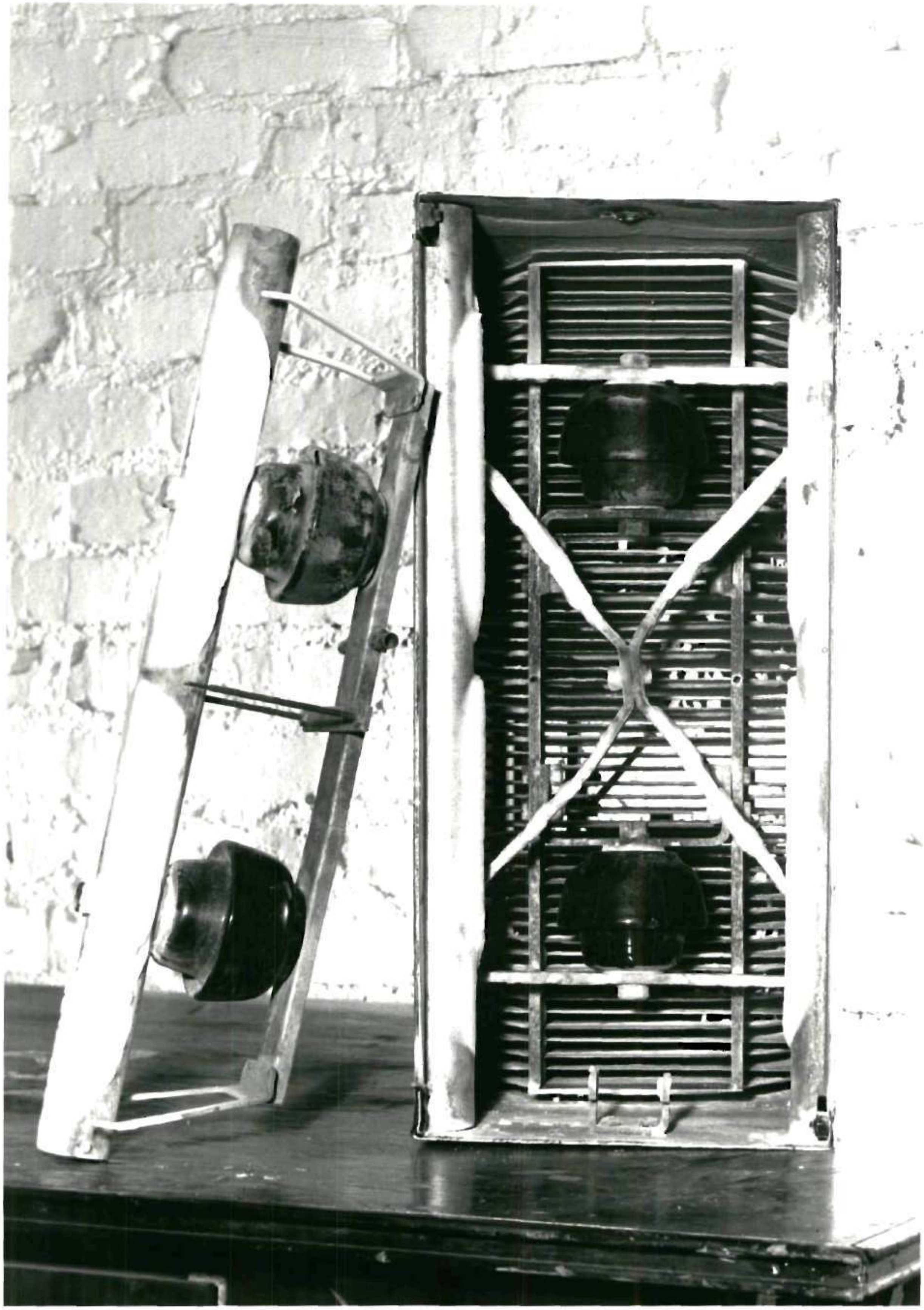


FIGURE 5

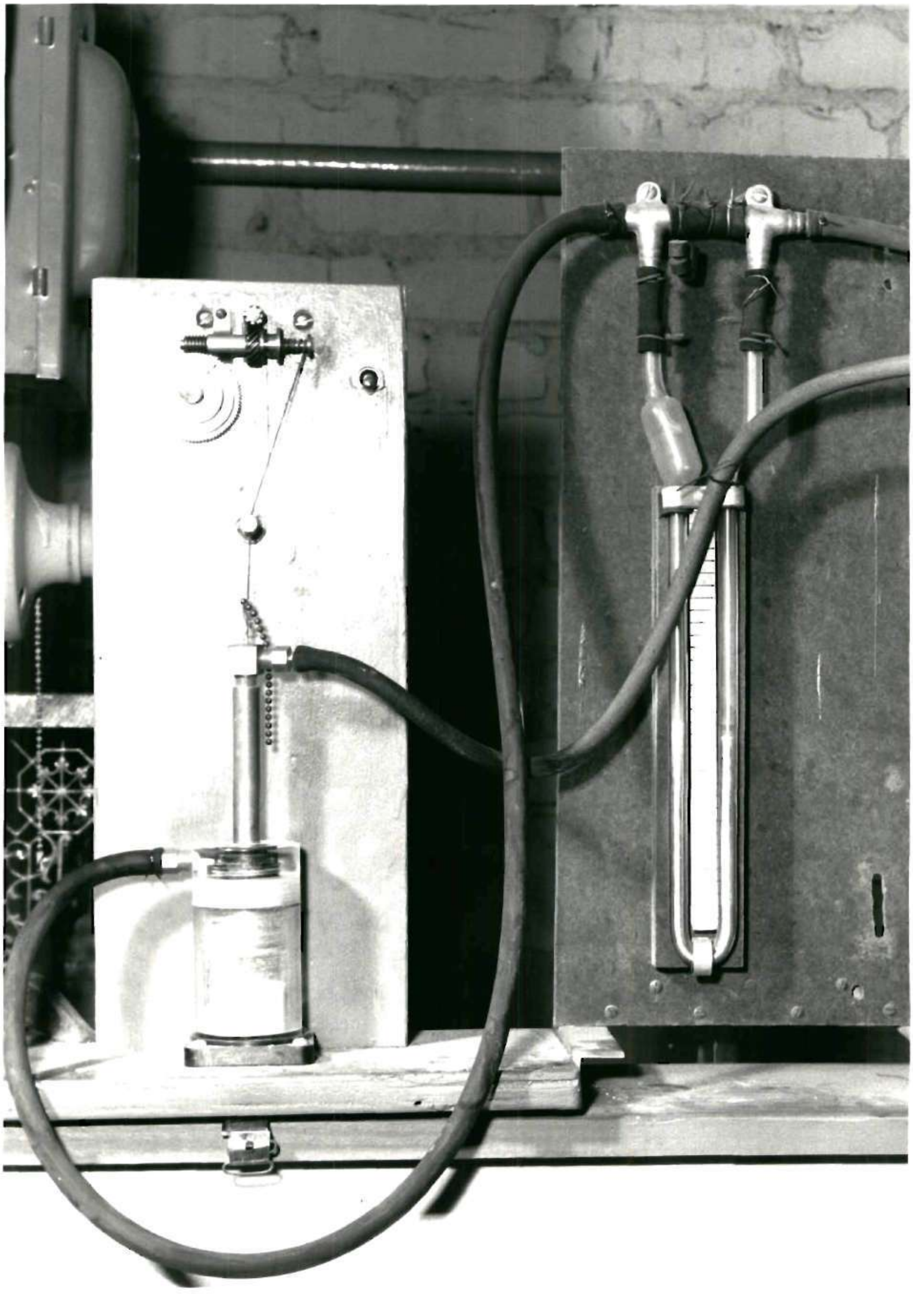


FIGURE 6

$\frac{1}{2}$ inch in diameter. A small hole is drilled through the center of the piston and rod to allow passage of air borne particles. The piston periphery is threaded with a double square thread to allow passage of air from the upper to the lower face. The system is provided with a 1 r.p.m. motor and pully arrangement for lowering the piston in the dust feed cylinder.

Air is introduced from a pressure reducing valve through a section of $\frac{1}{4}$ inch rubber hose to the upper face of the piston. The air then passes around the threaded periphery of the piston to the lower part of the cylinder and picks up dust particles, having acquired a swirling motion in passing around the piston periphery. The air borne particles then exit from the cylinder through the hole in the piston and rod to a section of $\frac{1}{4}$ inch rubber hose and thence injected into the PRECIPITRON blower suction. The rate of dust feed is controlled by varying the air pressure to the cylinder and the rate at which the piston is lowered.

Sampling Apparatus:

The sampling apparatus, Figure 3, consists of two circuits, each containing a glass sampling tube, a midget impinger, and a wet test meter. These elements are connected in series by short sections of $\frac{1}{4}$ inch rubber hose. One sampling tube was inserted into the air stream on the upstream side of the ionizer and collector sections, the other on the downstream. The terminal end of each sampling circuit was connected to the suction side of a small vacuum pump.

DISCUSSION

Procedure:

The dust used in this study was "Santocell", a product of Monsanto Chemical Company. This is a form of SiO_2, having a particle size of less than 3 microns (1 micron = 0.000001 meters).

A series of six runs were made to determine the effect of varying concentrations of air borne dust on the efficiency of the PRECIPITRON. Prior to these runs the ionizer and collector plate sections were thoroughly cleaned. The rate at which air was delivered to the unit was maintained at 588.4 c.f.m. during the entire series of runs. This rate was determined by use of an Alnor Velometer, type 3002. The ionizer section, collector plate section, and blower motor were energized shortly before the first run and remained energized until the last run of the series was completed.

The dust feed rate was maintained as nearly constant as possible during each run, thus the concentration of air borne particles may be considered constant throughout each run. The rate of feed was increased after each run, varying from a minimum value of 0.463 grams per minute, or 0.000788 grams per cubic foot of air, during the first run to a value of 1.0284 grams per minute, or 0.001747 grams per cubic foot of air, during the last run. These values are based on the difference in the weights of dust in the dust feed cylinder before and after the respective runs.

Each run was three minutes in duration. During each run samples were taken simultaneously from the upstream and downstream sides of the ionizer and collector plate sections, at a rate of approximately 0.1 c.f.m. The air borne dust particles were collected in 20 cubic centimeters of distilled water contained in the impinger tubes. After each run, samples contained in the impinger tubes were transferred to small glass jars which had been carefully rinsed with distilled water. The impingers were then rinsed and filled to the 20 cc marks in preparation for the next run. The only data recorded, other than the rate of feeds used in the first and last runs, were the differences in the wet test meter readings before and after each run. These differences are tabulated in Table 1.

The concentrations of dust particles contained in the impinger samples were determined for each run. These determinations were made by a modification of the microscopic, light field counting technique.[14] The equipment used included a Bausch and Lomb microscope; a 10x ocular provided with a standard Wipple disk; a Sedwick-Rafter counting cell, one millimeter in depth and with a volume of one cubic centimeter;

[14] Philip Drinker and Theodore Hatch, Industrial Dust (New York: McGraw-Hill Book Company, Inc., 1936), p. 117.

and a standard microscope lamp. The microscope was adjusted so that each square marked in the Wipple disk corresponded to 0.01 square millimeters on the stage.

Two cells were prepared from each sample and five fields, one centrally located and the others distributed toward the four corners of the chamber, were counted in each cell. Each field corresponded to 20 squares in the Wipple disk. Therefore:

$$C = \frac{N}{20x5x0.01x1} \quad X \quad \frac{20,000}{V_s}$$

where C = concentration of air borne particles in particles per cubic foot of air sampled

N = average number of particles counted per cell

V_s = volume of air sampled in cubic feet.

Values of the concentration of air borne particles on the upstream and downstream sides of the ionizer and collector plate elements were calculated for each run. These values are tabulated in Table I.

In this study, the efficiency of the model PRECIPITRON is defined as its effectiveness in removing air borne particles. Expressed mathematically

$$\text{Eff.} = \frac{C_u - C_d}{C_u} \times 100$$

where Eff. = PRECIPITRON efficiency in per cent

C_u = number of particles per cubic foot of air on the upstream side of the PRECIPITRON

C_d = number of particles per cubic foot of air on the downstream side of the PRECIPITRON.

Values for the PRECIPITRON efficiency were calculated for each run. These values are tabulated in Table I.

A run was made to determine the sparking characteristics of the collector plate section when a relatively high dust concentration is encountered. Prior to this run the ionizer and collector plate elements were thoroughly cleaned and the dust feed system was adjusted so that the rate of feed was slightly less than the maximum rate used in the efficiency runs. At this rate the dust feed cylinder was emptied in about four minutes. The damper in the blower intake was not disturbed. Therefore, 588.4 c.f.m. of air was delivered to the PRECIPITRON throughout the run.

The ionizer and collector plate units were energized throughout the run. However, the blower motor was turned off during the time required to replentish the dust feed cylinder. The dust feed cylinder was replentished from a known weight of dust in a container. At the end of the run the dust remaining in the container was weighed and subtracted from the original weight. The difference was the weight of dust injected into the blower intake during the run.

Dust was injected into the blower intake until excessive sparking occurred between the collector plates. The total time, i.e., the summation of the time intervals during which the blower motor was energized and dust was being injected into the blower suction, was recorded. Dust concentration in grams per cubic foot was calculated for this run using the following relationship:

$$C' = \frac{W}{588.4 \times t}$$

where C' = dust concentration in grams per cubic foot

W = weight of dust injected into the blower intake in grams

t = total time of run in minutes.

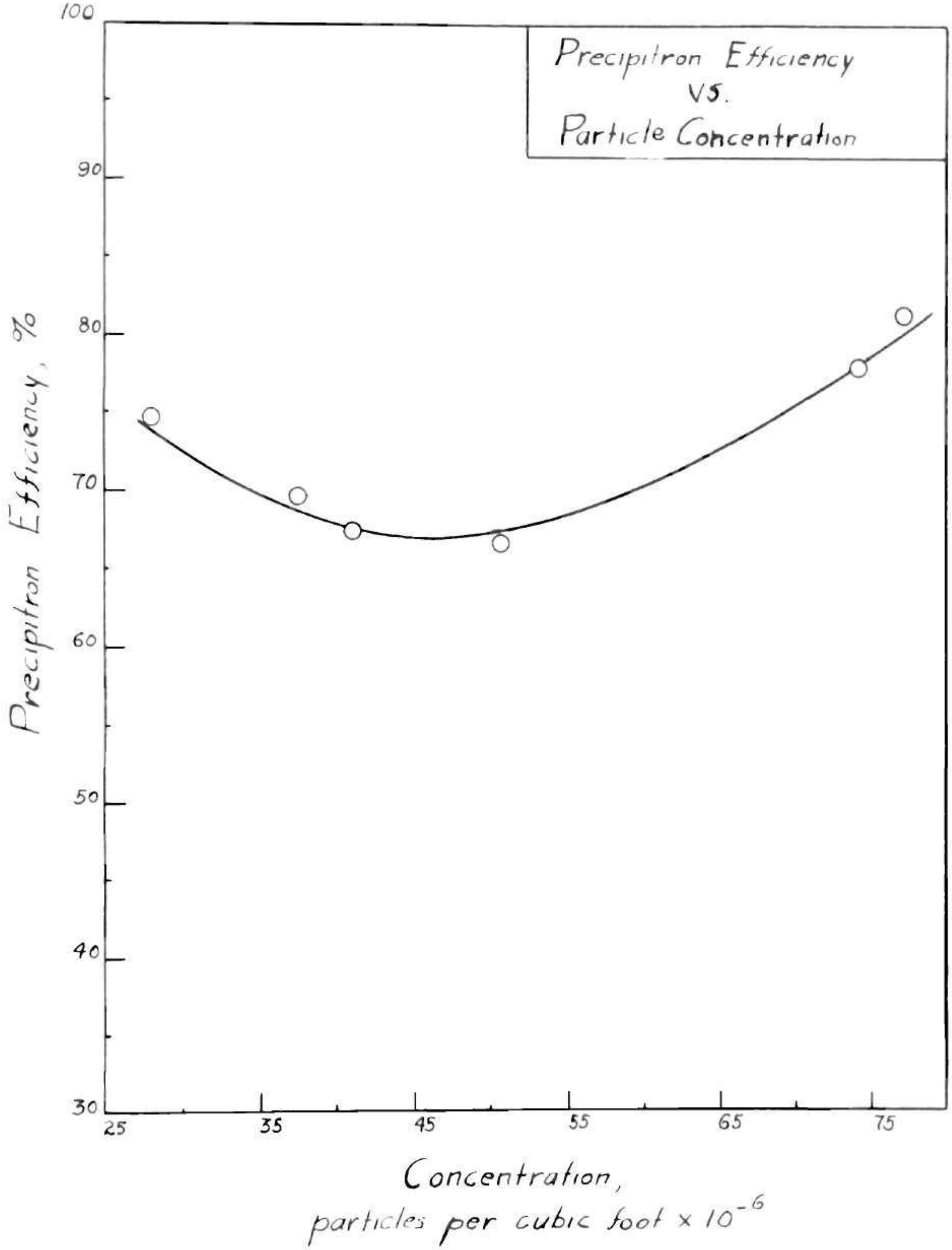
The results of this run are tabulated in Table II.

Results:

It was observed that a large percentage of the dust particles collected on the grounded tubes of the ionizer section and positive plates of the collector section. This is contrary to the theory of the PRECIPITRON.

A graph was plotted showing the variation of PRECIPITRON efficiency with dust concentration, Figure 7, from data tabulated in Table I. This graph shows that the efficiency of the PRECIPITRON decreases as the dust concentration increases from the minimum value used in this study to a value of approximately 47 million particles per cubic foot. At this concentration the efficiency reaches a minimum value and then increases with concentration.

In the run to determine the sparking characteristics of the collector section, sparking was negligible up to the point at which the unit had to be turned off because of excessive sparking. However, as the critical point was



Precipitron Efficiency
vs.
Particle Concentration
100
90
80
70
60
50
40
30
25
35
45
55
65
75
Precipitron Efficiency, %
Concentration,
particles per cubic foot x 10^-6

Figure 7

approached large lumps of dust were noticed to break away from the grounded ionizer tubes. Figure 5 shows the condition of the ionizer and collector plate sections after this run. It is estimated that 40% of the dust collected was collected on the grounded ionizer tubes. It is further estimated that 35% was collected on the positive plates of the collector section.

Conclusions:

(1) Efficiencies obtained in this study are considerably lower than those quoted by Westinghouse.[15] This difference may be explained, in part, by the difference in the properties of air borne particles ordinarily found in the atmosphere and the artificial dust used in this study.

(2) The large quantities of dust collected on the grounded ionizer tubes and positively charged plates of the collector section indicates that the ionizer section does not function properly when high concentrations are encountered.

(3) The shape of the PRECIPITRON efficiency curve is difficult to explain. However, it is believed that a detailed study of the behavior of charged particles in an electrostatic field would reveal an explanation. This would require a study of the net charge on the particles fed to the unit.

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[15] C. H. McWhirter and R. P. Posey, loc. cit.

(4) Due to the short period of time which the model PRECIPITRON used in this study may be operated before the collector plates require cleaning, it is doubtful that it would be either practical or economical to operate when high concentrations of air borne particles are encountered.

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APPENDIX

TABLE I: PRECIPITRON Efficiency Data.

RUN NUMBER	AIR SAMPLED, CUBIC FEET		AVERAGE COUNT, PARTICLES PER CELL		CONCENTRATION PARTICLES PER CU. FT.X10^{-6}		PRECIPITRON EFFICIENCY, %
	UP STREAM	DOWN STREAM	UP STREAM	DOWN STREAM	UP STREAM	DOWN STREAM	
1	0.3250	0.3030	473	112	29.13	7.40	74.64
2	0.3130	0.3415	588	194	37.57	11.36	69.76
3	0.3490	0.3530	720	237	41.26	13.43	67.46
4	0.2810	0.2885	711	284	50.61	16.92	66.57
5	0.2380	0.2650	884	216	74.29	16.30	78.06
6	0.2740	0.2825	1057	204	77.15	14.44	81.28

TABLE II: Sparking Run Data.

Total weight of dust	62.6815 grams
Total time	76.5 minutes
Weight/time	0.8193 grams/minute
Weight/volume	0.00139 grams/cu. ft.